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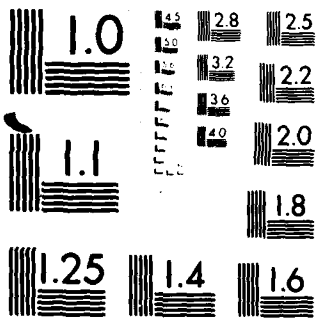

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User Requirements of Solar-Flare Predictions for Spacecraft Applications

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30 March 1981

Interim Report

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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This report is a preprint of the Working Group G report from the International Solar-Terrestrial Predictions Workshop held in Boulder, Colorado, in April, 1979. It addresses the current state-of-the-art in predictive capability in three areas of concern to spacecraft applications: the energetic particle environment; the plasma environment; and the neutral atmosphere. Recommendations are made for improvement of predictive capability in these areas. A centralized catalog of predictive techniques and models is also proposed.

PREFACE

This working group report was prepared by A. L. Vampola, Chairman, R. Altrock, W. Atwell, R. C. Backstrom, H. B. Garrett, D. Hickman, R. G. Johnson, N. H. Pereyaslova, D. Robbins, J. Slowey, J. Sroga, E. Stassinopoulos, M. Teague, and W. W. Vaughan.

This report is a preprint of the Working Group G report from the International Solar-Terrestrial Predictions Workshop held in Boulder, Colorado in April, 1979. This report will be published in Volume II of the Proceedings along with group reports from the other thirteen working groups at the Workshop. Review papers pertinent to the working group reports will accompany those reports in Volume II. Volume I is comprised of papers written by groups that routinely furnish predictions on the sun-earth system (solar activity, ionospheric conditions, etc.). A third volume will contain contributed papers and will appear substantially after the first two volumes. The Proceedings are being edited by Dr. Richard Donnelly of the NOAA Environmental Research Laboratories in Boulder and will be available in late 1979 or early 1980.

The working groups were:

A1	Long Term Solar Activity Predictions
A2	Short Term Solar Activity Predictions
B1	Interplanetary-Magnetosphere Interactions
B2	Geomagnetic Disturbance Prediction
B3	Energetic Particle Disturbance Prediction
C1	Magnetosphere-Ionosphere Interactions
C2	High Latitude E- and F-Region Ionospheric Predictions
C3	Midlatitude and Equatorial E- and F-Region Ionospheric Predictions
C4	D-Region Ionospheric Predictions
D	Solar-Weather Predictions
E	Communications Predictions
F	Geomagnetic Applications
G	Spacecraft Environment and Manned Spaceflight Applications

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1. INTRODUCTION

Our working group limited its scope to those areas which are influenced by solar-terrestrial coupling effects and are internal to the earth's magnetosphere. We did not consider, for instance, high altitude aircraft in the polar regions (exposed to solar protons at times of large flares) or missions to the moon or other planets, although they, too, are exposed to significant fluxes of energetic solar protons following proton flares. However, factors considered within the limited scope do have other applications and may address the above areas, although indirectly. Three subgroups were established which considered the areas of Energetic Particles, Plasma, and Neutral Atmosphere. Subsequent sections of this report deal with the requirements of users, the current status of models and predictive techniques, and future areas for research in each of these categories. Before we go into the detailed discussions however, we shall briefly discuss the types of users to be considered and the types of phenomena involved.

1.1 Users

Users of predictive techniques can be classified by the immediacy of their requirements. Operational programs, i.e., those which are currently engaged in a mission with spacecraft (manned or unmanned) already in orbit, have the highest requirement for accurate short and medium range predictions (24 hrs - 1 yr). Manned operations require real-time monitoring of solar parameters to deal with the possible threat of solar proton flares and magnetic field parameters to predict large scale energetic electron acceleration by major magnetic storms. In the event of a flare, predictive techniques must be available which, with high confidence, can detail the evolution of particle distributions at the spacecraft for minutes to hours and perhaps days ahead. If large space structures at synchronous altitude are serviced by men, the predictive techniques would have to extend to the evolution of the energetic particle population in the outer magnetosphere during and following magnetic storms. Other manned missions have similar requirements for other parameters. Another class of missions which require real-time monitoring and short time predictive techniques is that which includes very low altitude satellite orbits in which the atmospheric heating response to solar events produces significant increases in drag. For virtually every parameter under consideration, a mission can be envisioned which would require real-time or near-real-time monitoring of the parameter and accurate predictive techniques describing the temporal and/or spatial evolution of that parameter.

Presently, the operations people have limited predictive capability. Indeed they are forced to operate most often in the reaction mode and answer such questions as: a) How long will a proton or plasma event last? b) What is the intensity of the event? c) What effects will the event have on a particular system?

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The second class of users is that which encompasses those who require models or probabilistic predictions of a longer duration. Spacecraft hardware designers are an example. After a mission has been defined, i.e., orbit, launch date and flight duration are known, engineers require the tools to design a system which will survive and operate in the environment. An approach which uses either a worst case specification or an average-expected-environment-with-safety-factor model is usually satisfactory. In this instance, the requirement is not really for a predictive technique but rather an understanding of the upper and lower limits which a parameter may be expected to assume. Magnetospheric radiation belt modeling is an example of this approach.

A third category of user is the mission planner. He requires both a modeling capability and medium to long range predictions of solar effects. His selection of orbit and mission duration are governed to some extent by the typical environment which may be encountered, provided he knows sufficiently well what that environment might be. His selection of launch date (and perhaps mission duration) will depend upon his ability to predict the specific environment to be encountered at the time of launch. Manned missions, for instance, might not be launched at a time when a co-rotating solar proton source region was active on the sun if the mission used either a terrestrial polar orbit or one going beyond the magnetosphere.

1.2 Phenomena

Here we can discuss only those phenomena which we now believe to have deleterious effects upon spacecraft, their missions, and their occupants. From time to time new areas of concern are identified, either because the type of mission or orbit is new or a new technology is used which is susceptible to disturbance by a parameter which was previously thought to be either inconsequential or benign. The latest example is the 'soft failure' of logic elements in microminiaturized electronics. This will be discussed below.

1.2.1 Dose.

By 'dose' we refer to all phenomena in which it is the cumulative effect of ionization within an element (human cell, semiconductor junction) which causes damage. A related effect is the accumulation of free charge within insulators (i.e., cable dielectrics) and subsequent arcing which produces transients within the spacecraft electronics. The period of accumulation may be very long, as in communications satellites which have a planned life expectancy of seven to ten years, or very short, as in the case of an astronaut on an EVA (Extra-Vehicular Activity) at a time when the natural environment might subject him to a skin dose rate of several hundred to a thousand rems per hour. The specific case of dose considerations in manned missions is addressed in a short contribution by Atwell (1979), Stassinopoulos (1979) and briefly by Johnson et al. (1979) in these proceedings. We should point out that greater accuracy is required for calculations of dose for manned missions than for unmanned, since there is less variation in dose tolerance and the consequences are more critical in man than in components.

1.2.2 Charging.

In the presence of a 'hot' plasma, a spacecraft can charge to significant negative potentials due to the much greater mobility of the electrons than the ionic constituent of the plasma. The resulting charge on the spacecraft can lead to a number of

deleterious effects, some of them potentially lethal to the hardware. The negative potential may enhance the accumulation of contaminants by spacecraft surfaces through the mechanism of outgassing, photoionization of the outgassed molecule, and re-attraction by the potential on the spacecraft. Thermal control surfaces, especially second-surface mirrors, optical devices and certain sensors are particularly vulnerable to this type of degradation. If the spacecraft is in sunlight, photoemission of electrons from the sunlit portions of the vehicle may neutralize the charge build-up due to the plasma. The self-shadowed portions of the vehicle, unless they are electrically conducting and connected to a sunlit conductor, will remain at high negative potential. The potential difference between these differentially charged surfaces may result in an arc which could interfere with the operation of the vehicle or even destroy a critical component. An EVA at synchronous orbit could result in some rather spectacular (and perhaps tragic) events if this phenomenon is not considered in the design of the spacesuit and the EVA itself. Perhaps real-time monitoring of electron pitch-angle distributions (see Baker et al., 1979) will be required to predict the onset of substorms (and their injection/acceleration of hot plasma into the region of the large space structure being serviced) if the synchronous orbit becomes populated by structures serviced by man. The charging phenomenon is not now well understood, but the SCATHA (Spacecraft Charging at High Altitude) program, with the quasi-synchronous spacecraft P78-2, is now investigating the problem both in the lab and in space and will perhaps eventually provide both an understanding of the phenomenon and quantitative models for predictive purposes.

1.2.3 Neutral Atmosphere

An important use of models of the neutral atmosphere above 100 km has been in the general area of prediction of satellite orbit evolution. The upcoming demise of Skylab has focussed public attention on both the importance and limitation of our ability to predict satellite drag. The economic cost of inaccurate orbit decay predictions can be substantial. Other important uses of the models can be found in such areas as the planning of scientific missions; the interpretation, reduction, and analysis of experimental results; and the development of models relating the neutral upper atmosphere to the ionosphere and magnetosphere.

The MSIS model (Hedin et al., 1977a, 1977b) and the most recent Jacchia model (Jacchia, 1977) are both capable of representing the density and composition of the thermosphere and exosphere with an accuracy approaching that of the available observational data, at least for time-scales of a day or more. Of these two models, the Jacchia model represents the geomagnetic variation more accurately, while the MSIS model represents the diurnal variations more accurately in the lower thermosphere. Both models can be improved in these two areas and work is in progress to accomplish this. The CIRA 1972 model (COSPAR, 1972) continues to be useful in providing estimates of total atmospheric density for heights above 200 km. However, this and other older models do not correctly represent the strong dependence of the geomagnetic variations on geomagnetic latitude.

Current neutral atmosphere models reflect the available measurements very well and use the $F_{10.7}$ and A_p or k_p indices to indicate the amount of energy input into the thermosphere. If present neutral density models are to be used in making predictions, therefore, there must exist a significant ability to predict these indices. There is only very limited current capability in predicting these indices and we have not seen much promise for greatly improved prediction ability in the near future.

It is clear that even with improved capability to predict A_p and $F_{10.7}$, substantial model improvement must depend on utilization of parameters which more directly measure the thermospheric energy sources. If models which use these improved parameters are to be developed it is essential to ensure that future satellite missions simultaneously measure the energy inputs and the ensuing atmospheric response.

1.2.4 Soft Failures

The increasing use of very high density micrologic in spacecraft systems has introduced a new concern of solar influences. A relatively low energy ($\approx$ 2 MeV/nucleon) high-Z (Fe, for instance) cosmic ray has sufficient specific ionization rate that the energy deposited in a microjunction can cause a change of state of the device (a 'bit-flip'). In some cases, the result may be a 'latch-up' which destroys the device, but usually the only result is a bit error in the spacecraft logic. The error may be unnoticeable in the data or may result in loss of a spacecraft function. Typical results for some tested devices range from no susceptibility to one bit flip per bit per 10^4 days (equivalent to 4 bit-errors per hour for a megabit memory). This phenomenon is discussed by Sivo et al. (1979) and test results are presented by Kolasinski et al. (1979). A prediction capability for solar flares rich in high-Z nuclei should be developed to cope with this effect.

1.2.5 Background/Interference

These effects are due to the same type of interaction discussed under Dose and Charging, but are distinguished from them in that they result in no permanent damage to a system. They merely degrade data or make a spacecraft subsystem temporarily inoperable. These subsystems usually include a sensitive detector of one sort or another. The famous star-sensor that lost lock on Canopus every time an energetic proton mimicked the light output from the star is a good example. Another is the X-ray telescope that was swamped by background counts each time it went through the South Atlantic Anomaly. Usually, sensors are designed to work in spite of these background effects; however, the environment and variations in it must be accurately predicted in order to do the necessary design.

2. USER REQUIREMENTS OF SOLAR-TERRESTRIAL PREDICTIONS FOR SPACECRAFT APPLICATIONS: ENERGETIC PARTICLES

Prepared by the Energetic Particles Subgroup: A. L. Vampola, Chairman, W. Atwell, R. C. Backstrom, R. G. Johnson, N. H. Pereyaslova, D. Robbins, J. Sroga, E. Stassinopoulos, and M. Teage

In this section we consider all particles which produce deleterious effects through energy deposition. In general, electrons below 50 keV and protons below 100 keV are not in this category. However, for certain applications, these energies are sufficient to cause direct damage; in those instances, we include them in our discussion of predictive techniques. Modeling is considered one form of prediction and will be treated as such.

We shall subdivide the energetic particle discussion into categories based on two distinct parameters: Physical location and particle energy/type. The requirements for predictive techniques and the state of the art differ markedly for the inner magnetosphere, the outer magnetosphere, low polar orbit, interplanetary trajectories, and

earth's magnetic field during the diffusion period (since it is the magnetic behavior that is driving the diffusion). The outer zone electron population is itself a response to earlier magnetic field behavior. Predictive techniques which are required to provide a knowledge of the outer zone electron flux will be discussed later. At our present state of knowledge of interactions between the solar wind and the magnetosphere, it is unlikely that we will be able to predict, in the foreseeable future, geomagnetic activity with sufficient accuracy to enable a prediction of energetic electron transport into the inner zone. (The above statement is partially based on our current lack of a detailed understanding of loss processes in the slot region.) It should be pointed out that natural sources of electrons with energies above 1 MeV would supply orders of magnitude less flux in the inner zone than was injected by the Starfish nuclear event. Spacecraft and sensors were designed to be operable in the remnants of that injection during the mid-Sixties and could again be made so.

To summarize for the inner-zone orbits: Models are currently adequate and constitute all of the predictive techniques currently required. A better understanding of particle transport through the slot region into the inner zone would, in special cases, be useful, providing that the outer zone electron population were known at the same time. This indicates a need for either a sophisticated prediction scheme for outer zone electron acceleration and transport or a real-time monitoring system. The utility of the data for inner-zone purposes does not warrant the expenditure necessary to obtain it. (There are strong reasons for obtaining the data for outer zone missions; hence, the data may be available essentially 'free'.)

2.1.2 Low Altitude Polar

For polar orbits, all of the above considerations apply, since a satellite in low polar orbit spends about 40% of its time in the inner zone. It also spends about 25% of the time in the outer zone and 35% in polar regions. This could be considered a 'composite' orbit which includes aspects of the inner zone, the outer zone, and interplanetary missions. The additional requirements for this orbit can be obtained from the following sections which address the outer zone and interplanetary missions.

2.1.3 Outer Zone

The situation in the outer zone is much more complex than in the inner zone. The principal reason is that it is much more dynamic. The electron component has a relatively short residence time in the magnetosphere (decay times of the order of a few to tens of days) but the source activity has commensurate time periods. Sources may be particles injected from the tail coupled with radial diffusion as an accelerator or in-situ acceleration by non-adiabatic means. Energetic electrons in the inner region of the outer magnetosphere can change by orders of magnitude in flux level over periods of less than a day. (See Vette et al., 1979). The situation with regard to protons is somewhat better.

From the point of view of the user, the primary areas of interest are the variability of the energetic electron fluxes and the access of solar protons. Solar protons do not constitute a significant portion of the dose to a spacecraft for a long term mission except for interplanetary missions. However, for short periods, they can constitute a sizeable portion of the dose-rate. The predictive capability which is needed in this area is the following: Given a solar flare on the sun, predict the fluence and spectrum as a function of time and L within the magnetosphere. A desired goal is the capability to predict the flare, itself, from the features on the sun and the sun's

planetary encounters. Low polar orbit and interplanetary trajectories share a common concern for solar proton flux predictions. We will not address planetary encounters. Basically, particles will be divided up into electrons and protons (and other ions); energies will be low (up to 500 keV for electrons and 5 MeV for protons), medium (to 2 MeV for electrons and 50 MeV for protons) and high (everything above medium). We will also consider particle origin and transport as needed.

2.1 Magnetospheric Zone

2.1.1 Inner Zone

For our purposes we shall consider the inner zone to be all altitudes and latitudes below L=2. (L is McIlwain's parameter and in a dipole field corresponds to the radial distance from the center of the earth to the equatorial crossing of a given field line. Units are in earth radii.) The effects which are important in this region are dose effects to man and components, background effects in sensors, and transient upsets in logic due to high-Z events as discussed in the introduction. If we initially limit our discussion to low inclination orbits, we don't have to consider solar and galactic cosmic rays. Presently, there is no knowledge of significant fluxes of high-Z nuclei with energies in the MeV per nucleon range in the inner zone. For polar orbits, we will have to consider these particles.

The prediction of particle fluxes in the inner zone is in excellent shape with the radiation models issued by the National Space Science Data Center (see the review by Vette et al., 1979). The modeling of energetic protons in the inner zone up to hundreds of MeV has progressed to the point that the prediction is probably as reliable as any given single measurement of the flux. At the lower altitudes (< 1000 km) the latest models include solar-cycle effects. The prediction of dose due to energetic protons under thick shields is certainly better than a factor of two and is probably within the 25% range for reasonably long duration missions. The low energy proton population (< 5 MeV) is subject to significant temporal variations but the cumulative effects from this portion of the particle environment are small compared to those from the higher energy population. To summarize the state of predictive capability in the inner zone proton population, the models are adequate for all present missions and may be presumed to be correct unless new <u>reliable</u> data are obtained to the contrary. The weakest area of knowledge is the regime covering the energy range above a few hundred MeV. Spectra, pitch-angle distributions, and flux intensities could be used in sensor design and background estimation if they became available. However, we know of no present or future mission for which such information would provide primary design criteria.

In the inner zone, the electron modeling situation is also excellent. Fluxes above 1 MeV are sufficiently low at all times that for most purposes they can be ignored. Substantial fluxes of lower energy electrons are subject to significant variations only on time periods commensurate with the solar cycle. At times of very large magnetic storms, a small fraction of the energetic outer zone flux succeeds in diffusing through the slot region. Electrons with energies up to 1.5 MeV have been traced in to as far as L=1.55. But the contribution of these particles to the total dose in inner-zone orbits is negligible. They can constitute a significant increase in background for some sensor systems. Prediction of such events would be useful but presently is not essential. Any predictive technique would probably require as inputs a knowledge of the energetic electron population in the outer zone and a detailed knowledge of the behavior of the

immediate past behavior. Both of these predictive capabilities may still lie far in the future. However, an immediate goal should be to obtain sufficient understanding of the physics of the entry process to be able to perform the first stated prediction once a measurement of the proton flux has been made in interplanetary space between the earth and the sun. At the present time, even this capability does not exist. Our present knowledge extends only to entry into the polar caps and entry to the synchronous altitude. Even that capability is uncertain.

To obtain the physical understanding, we need more analysis of the data that has been obtained which can address the topic (such as the Explorer 45 data base) and we need a properly instrumented satellite which covers the L range from 3 or 3.5 to at least 8. Pitch angle distribution data are required in order to determine the off-equatorial progression for solar proton flux injections.

2.2 The Requirements for Modeling and Prediction of Geomagnetic Storms

The importance of temporal variations in the trapped electron population in the slot and outer zone regions is qualitatively well known. In assessing the qualitative consequences of this on the modeling, forecasting, and user communities, it is important to be as restrictive as possible by focusing on user requirements in order to avoid unnecessary activity in the modeling and forecasting fields. It is now recognized that there are regions of the radiation zones in which the time scale of temporal variations is of the same order as the mission duration. As a result, missions which accumulate a significant flux contribution from these regions are not well served by the present generation of trapped electron models which contain time averaged representations of the particle population. In this role we focus on two sample missions in this category (noting that others exist) for which the requirements on the modeling and forecasting communities are radically different, partly on pragmatic grounds and partly as a result of differing user needs. The first is the normal mission analysis activity several years before launch, which is performed to predict the radiation environment. The second is EVA activity performed in association with man's presence at synchronous altitude.

In the first case, missions spending significant time in the L region of 3 to 5 may encounter an average flux over a 3-6 month period different by a factor of 4 or 5 from the flux 'predicted' by a model developed with the current technique of time averaging the data. The occurrence or lack of a storm event and the event size are the deciding factors . All that is positively known at the present time is that the mission has been shielded for a situation that is either unduly pessimistic or optimistic. The solution is to account for the effects of individual events. But to what extent? It is clear from the working group sessions that it is impractical to try to predict the occurrence of a single event in a given 3-6 month period with a lead time of years. It is questionable whether this can even be done meaningfully (i.e. quantitatively) with a lead time of hours (Higbie et al. 1979), hence for the long-term planners the question of prediction may be moot. This, however, does not mean that design should occur with respect to a worst case situation. As a realistic objective it should be possible to achieve two situations: 1) given rapid access to a ground based magnetic index (Dst?) to infer the peak storm flux to within a factor of 2-3 at any given L and the time of occurrence of the peak flux, and 2) by modeling the depletion phase of the storm to develop the time history of the flux at the satellite. This may be practical without an overwhelming modeling activity; however, does it have value to the mission planner? In some respects the answer may be no. The mission planner may require a model which can provide the

probability of occurrence of an event of given size in the mission period (not necessarily an easy task for modelers because of the number of observations - presently 7-10) and the event integrated flux resulting from the event. No per event prediction is involved per se. In some respects the answer to the question may be yes. If the above nominal radiation environment is assessed the nominal lifetime could be predictively updated in the event that a magnetic storm occurs; i.e., one could predict the demise of the mission. This implies a more rapid response from the modelers or the model users than presently exists. Further the value of this prediction to a military application is questionable unless a rapid launch capability exists.

In the second application, EVA activity at synchronous altitude, the role of prediction is a little clearer. The present generation of time-averaged models indicates that an EVA activity with .2 gm/cm^2 Al shielding (equivalent of the average space suit) reaches the currently valid mission radiation limit for a 90-day skin dose of 105 REM (about 81 rads Al) after only 1.35 hours of cumulative exposure. At the same time it is known that several orders of magnitude excursions of the flux occur around the average. The implications of a positive excursion are severe. The corollary is that the negative excursions, which persist for periods sufficient for individual EVA activity, have great potential. For this application ideally one needs to predict the onset and duration of a quiet period with sufficient lead time for scheduling EVA activity. Predicting the onset is practical and involves the definition of the depletion phase of a previously occurring storm. Prediction of duration may not be feasible explicitly. However, the working group on energetic particles has investigated the short-term prediction of the onset of a storm. If this is feasible, the appropriate question is the lead time of the prediction and the relationship to the time required for the EVA operator to reach shelter. Note that the prediction of the magnitude of the potential event is relatively unimportant since shelter must be sought irrespectively. However, the magnitude of the event would relate to the prediction of the onset of a quiet period. For large solar arrays several km in dimension the transit time to reach shelter may be several hours. Prediction of onset with this much lead time seems to be difficult. For large structures, transporters more heavily shielded than suits may be required to circumvent the problem.

The above applications relate to total dose. For rate dependent problems it may be possible to provide sufficient prediction time to influence operational scheduling in a meaningful way. As with the EVA activity, prediction of onset of a certain rate may not be possible with sufficient lead time for scheduling. However, a sufficient prediction of the time for the flux to return to a rate commensurate with equipment operation could be provided.

Almost all of the applications discussed above involve not only a predictive capability but also the ability within the modeling community to generate model fluxes on short notice. A new generation of model service is required in which models with some per-event flux capability are on-line on a computer with close operational links to both the mission project offices and the organizations generating the parameters to be used for prediction.

Again, almost all of the above applications require a knowledge of not only the flux at a given point in time but also at a given point in space. The present models are used in a local-time-averaged form by most users although a local time variation is available. The shielding community should investigate the use of the various L parameters including external magnetic field effects as a method of ordering particle data in the outer zone, eliminating the need for a local time variable. An additional

benefit would be a parameter simplification of the models in a spatial sense. It is noted that this general point has application to geosynchronous EVA activity since, although the satellite local time averages on a daily basis, the EVA activity of several hours duration may have a significant local time bias.

2.3 Energetic Solar Flare Proton Predictions

The integrated flux during the first four days after the August 1972 solar proton event exceeded the previous 11-year cycle integrated flux. In order to improve on the ability to predict the occurrence of these anomalously large (AL) events, it would be advantageous to investigate whether their occurrence correlates to any solar parameter or other observable solar phenomenon or event, and whether reliable precursor conditions can be established, of the order of hours-to-days, to be used for predictive purposes of AL events.

The calculation of event integrated annual totals of unattenuated, interplanetary solar flare proton fluxes at 1 AU for energies greater than 10, 30, and 60 MeV, from measurements obtained by the IMP series of satellites, demonstrated that these annual totals do not correlate well with sunspot numbers. It may be useful to investigate whether the actual occurrence of solar flare protons at 1 AU may be more reliably and accurately correlated to some solar parameter or phenomenon other than sunspot numbers.

Finally, penetration of solar flare particles into the magnetosphere needs to be considered in view of the following facts: a) local time variations of geomagnetic cutoff latitude are about 3-4 degrees, and b) storm effects can change these latitudes by up to about 2-4 degrees. These two variations are additive. Rigidity and geomagnetic shielding evaluations should take these variations into account. Preliminary estimates indicate that very significant differences in exposure values may result from this improvement.

2.4 Time Variations

For purposes of long-range mission planning (e.g. variable crew station periods, etc.), it may be useful to know whether a significant ($\geq$ factor of 3) variation in the environment of critical duration (critical $\approx$ 30 to 60 day duration or periodicity) can be established, in order to bring crew schedules into phase with phenomena.

This is presently not possible since these variations, which may be large, appear to be stochastic. However, correlation with, for instance, fast solar streams may provide a mechanism for predictions. Decay is an important factor. Significant work is required in this area.

3. USER REQUIREMENTS OF SOLAR-TERRESTRIAL PREDICTIONS FOR SPACECRAFT APPLICATIONS: PLASMA

Prepared by the Plasma Subgroup: H. B. Garrett, Chairman, J. Sroga, and A. Vampola

In the last few years an increasing emphasis has been placed on interaction between the low energy (10 eV - 100 keV) near-earth plasma environment and space systems. In parallel with this growth in emphasis has been a need for predictions of the

low energy plasma. As discussed in the review by Garrett (1979) these predictions are necessary because of the effects of a number of interactions. The Plasma Subgroup has attempted to summarize these interactions and identify the idealized parameters needed to understand and predict these interactions.

3.1 Basis of Requirements

The number of known interaction mechanisms between the low-energy plasma environment and space systems has steadily grown. Ranging from the effects of static charge buildup on satellites to the effects of argon beams on the plasmasphere, these interactions all have in common the necessity of knowing the distribution function of the ambient environment and how it evolves in time. The plasma subgroup has reduced the many interactions down to two primary types of effects. The primary effects and the specific aspects of the distribution function required are as follows:

1. Spacecraft charging - the process of charge buildup on spacecraft is not completely understood (specifically the arcing process and the plasma environment are not predictable at all). As a result, detailed knowledge of the distribution functions and composition as functions of time and position should be acquired until the critical parameters are identified. As discussed in Garrett (1979) and Garrett et al. (1979), however, the charging models at present require only the electron and ion currents and electron temperature. These quantities can be estimated either by statistical tables or by A_p. The detailed models of the environment will be required if any improvements are to be realized over these present models. It should be emphasized that in addition to the need to model the large scale plasma distributions within the magnetosphere, it is also essential to understand and to model the smaller scale characteristics of the hot plasmas (Johnson et al., 1977). For example, the charge distribution on a spacecraft could be greatly influenced by the highly anisotropic field-aligned electron and ion fluxes frequently observed as a plasma feature at geosynchronous altitude (McIlwain, 1975) and at lower altitudes over a wide range of L-shells and local times (Johnson et al., 1977). Also, the ionospheric components (O^+ and H^+) which are sometimes dominant in the hot plasmas can be highly structured spatially and/or temporarily (Geiss et al., 1979).

2. Contaminants - calculation of the deposition of ionized contaminants on spacecraft requires knowledge of the ambient particle distribution to determine not only the charging on satellite surfaces to which contaminants are attracted, but also the rate of ionization (Cauffman, 1973). The related problem of contaminant cloud propagation in the plasmasphere and magnetosphere (Chiu et al., 1979) requires detailed knowledge of the ambient population and, in order to estimate the evolution of the contaminants, the electric and magnetic fields - parameters dependent on geomagnetic activity.

The user groups can likewise be divided into two basic groups. The first group consists of the designers who are primarily interested in the specification of the space environment. Not only are they interested in specifying the geophysical environment before building a system in order to protect it from the above effects, but, as is often the case, also the specification of the environment for the purpose of investigating anomalies resulting from them. The second group is composed of forecasters - those who must predict when the anomalies may occur. This latter group is interested in two time periods. First, there is long-term prediction of 3 years or more for mission planning, and second, there are short-term (24 hour to 1 year) predictions. This last group is of most concern to this conference. Specific questions to be answered

are: a) How long will the plasma event last? b) What are the characteristics (composition, energy, and angular distributions, etc.) of the event? c) What effects will the event have on a particular system?

3.2 Requirements

From the preceding descriptions of interaction phenomena and of the user groups and required time scales, we believe it is evident the plasma distribution function and its evolution in time (or equivalently the electric and magnetic fields) are required in great detail - detail that is clearly not attainable now or in the near future. Thus simplification must be introduced. These are primarily real-time (either in-situ or from solar wind parameters) estimates of the environment and/or detailed statistical models of the plasma distribution function in terms of predictable parameters such as A_p. It is to this end this subgroup recommends current efforts be directed. Our state of knowledge in these areas is evaluated in the other working group reports.

4. USER REQUIREMENTS OF SOLAR-TERRESTRIAL PREDICTIONS FOR SPACECRAFT APPLICATIONS: NEUTRAL ATMOSPHERE

Prepared by Neutral Atmosphere Subgroup: W. A. Vaughan, Chairman, R. Altrock, D. Hickman, D. Robbins, and J. Slowey

Orbital altitude total density and constituent number density variations are a direct function of the short- and long-term fluctuations in solar activity. These variations are due to the heating of the Earth's upper atmosphere by solar radiation and energetic particles. The importance of these variations is found in the requirement for orbital performance capabilities which will insure design lifetime, definition of orbital dynamics for nonspherical spacecraft, assessment of lifetime potential for spacecraft in orbit, and scientific experiments. Estimates of short- and long-term solar activity levels are critical inputs to these calculations.

4.1 Basis of Requirement

While there is a variety of users for neutral atmosphere models, we believe that their needs are reflected by the requirements of those using the models for orbital lifetime calculations. Therefore, this paper focuses on orbital lifetime prediction requirements.

A semi-analytical method is used in most spacecraft orbital lifetime prediction models to estimate the decay history and the lifetime of a near-Earth orbiting spacecraft perturbed by atmospheric drag. For most near-Earth orbits with small eccentricity, the perturbations due to other forces (i.e., solar-lunar gravity perturbations, solar radiation pressure, and electromagnetic effects) are overshadowed by the effects caused by uncertainties in the calculation of atmospheric drag. For this reason, efforts to incorporate additional perturbing forces are often unwarranted. The approach used to estimate the orbital decay usually adopts a combination of general and special perturbation techniques so that the analysis preserves sufficient rigor to insure accuracy and adequate numerical emphasis to include a rather sophisticated atmospheric density model in an efficient simulation. Basically, the procedure is to extend a system of ordinary differential equations for a set of well-defined mean orbital elements which describe the complete motion of a spacecraft about an oblate

Earth to include numerically the drag effect due to a rotating atmosphere. The program is designed to estimate, with reasonable accuracy, the orbital decay history and the orbital lifetimes efficiently and quickly. Figure 1 illustrates the principal inputs and components of a spacecraft orbital lifetime and decay prediction procedure.

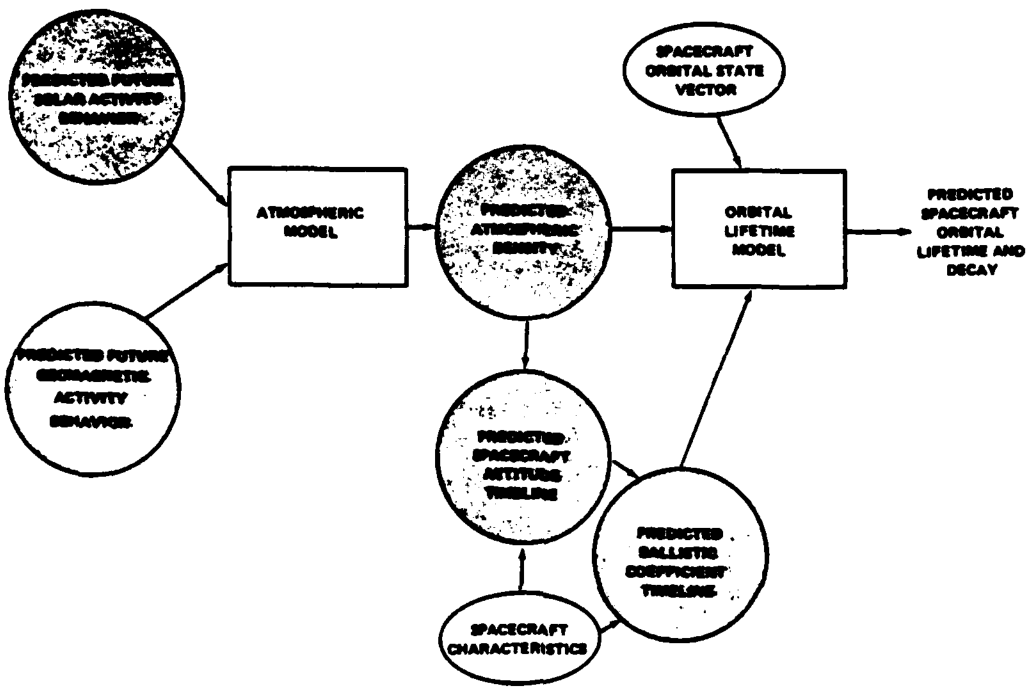

Fig. 1. Solar Predictions and Spacecraft Orbital Lifetime

A major difficulty in predicting orbital lifetimes arises because the future characteristics of the atmospheric density are not deterministically known. This makes it necessary to specify orbital lifetimes in a probabilistic manner. Comparisons of predicted spacecraft decay versus actual observed decay reveal deviations which can be attributed to an inadequate deterministic atmospheric model, noisy tracking data, or deviations in the stochastic variables associated with the lifetime prediction problem (i.e., ballistic coefficient, solar flux, and geomagnetic activity). The ballistic coefficient is a function of the spacecraft mass, drag coefficient, and effective cross section area. It is observed to vary with the spacecraft orientation and flight region. In addition, predictions of the solar flux and geomagnetic activity values, over either short or long periods of time, are available only in terms of statistical predictions with significant uncertainties.

Straus and Hickman (1979) describe the characteristics of several widely used atmospheric density models and have reviewed studies in which the predictions of these models have been compared with observational data. They also assess the relative advantages and limitations of the models in current use. They conclude that models produced prior to 1970 were developed from data bases with significant limitations. The overall accuracy of the recent models is summarized as being, on the average, as good as the measurements of atmospheric density and composition. This is evidenced

by the fact that some measurements have a mean deviation slightly higher while other measurements have a mean deviation slightly lower than the model calculations. We interpret this situation as being due to systematic instrumental inaccuracies. However, instantaneous measurements show a scatter of about a factor of two compared with the model calculations of atmospheric parameters.

The upper atmospheric density is strongly influenced by the changing levels of solar activity. This, in turn, directly affects the spacecraft drag and orbital lifetime. It is the ultraviolet solar radiation that heats and causes structural changes in the Earth's upper atmosphere. One component of this radiation relates to the active regions on the solar disk and varies from day to day, whereas the other component relates to the solar disk itself and varies more slowly with the 11-year solar cycle. Another influence on atmospheric density is due to energetic particles emitted by the sun as evidenced in the solar wind number density and velocity. These energetic particles are ultimately responsible for heating the Earth's upper atmosphere. The atmosphere reacts differently to each of these parameters and components (NASA, 1973 and Jacchia, 1977).

The 10.7 cm solar flux is generally used as a readily available index of solar ultraviolet radiation. It also consists of a disk component and an active region component. When the 10.7 cm flux increases, there is an increase in the upper atmosphere density. For a given increase in the disk component of the 10.7 cm flux, however, the density increases much more than for the same increase in the active region component. For all practical purposes the active region component is linearly related to the daily 10.7 cm flux and the disk component to the 10.7 cm flux averaged over a few solar rotations (e.g., six is used by Jacchia (1977)). The planetary geomagnetic index is generally used as a measure of the energetic particle heating. When the geomagnetic index varies we observe a density variation with a time lag of about 3 to 8 hours depending upon latitude.

An error, for example, of + 30 percent in the prediction of the maximum in the mean 10.7 cm flux during the ascending slope of the solar cycle, for a spacecraft at approximately 400 km altitude and having a nominal predicted lifetime of approximately 20 months, produces a decrease in the lifetime of approximately 30 percent. While this linear error relationship does not hold for all combinations of variations in solar activity, orbital altitudes, and ballistic factors, the example does illustrate the importance in the development of either a deterministic long-term solar activity prediction procedure or a statistical procedure with much closer confidence (error) bounds than now exists.

4.2 Requirements For Solar Activity Predictions

There exists a critical need for more accurate predictions of short- and long-term solar activity to use in atmospheric density models. This will be required not only for the monitoring and accurate estimation of the orbital lifetime and decay for the large numbers of spacecraft and "junk" now in orbit but for the more economical and efficient estimation of future spacecraft missions, especially in the near-Earth orbital environment. The expected future state of the upper atmosphere plays an important part in the decisions associated with spacecraft missions. The critical dependence on solar activity predictions can easily be seen by looking at the flow chart shown in Figure 1.

That a neutral atmosphere model must be accurate is obvious. Less obvious is

how the accuracy is to be characterized for a particular use. A perfect description of the atmosphere is the ideal, but some kinds of inaccuracies are unimportant for specific applications. A spacecraft designer who is required to provide an orbital altitude capability for a two year lifetime may be quite satisfied with a model output having the correct mean value when averaged over a month's time span even if the errors averaged over a single orbit are quite large. On the other hand, a tracking station operator or mission monitor concerned with spacecraft decay within a few days or weeks may attach no importance at all to the long-term mean behavior of the atmosphere if the model output can accurately predict the short-term variations.

Current neutral atmosphere models employ 10.7 cm flux and geomagnetic index (A_p or k_p) as heating indicators for model inputs. The solar-terrestrial prediction requirements to meet most user needs are given in Table 1.

Table 1. Solar-Terrestrial prediction requirements.

Approximate Prediction Period	Critical Parameter	Accuracy	Resolution	Frequency of Update
Very Short-Term (< 1 mo)	$F_{10.7}$	5%	6 solar rotations	Weekly
	$F_{10.7}$	5%	Day	Daily
	A_p	5%	Day	Daily
Short-Term (1-2 mo)	$F_{10.7}$	5%	6 solar rotations	Monthly
	$F_{10.7}$	5%	Day	Weekly
	A_p	5%	Week	Weekly
Long-Term (≥ 3 mo)	$F_{10.7}$	10%	6 solar rotations	Quarterly
	$F_{10.7}$	10%	Week	Monthly
	A_p	10%	Quarter	Quarterly
Long-term (≥ 1 yr)	$F_{10.7}$	10%	6 solar rotations	Yearly
	A_p	10%	Year	Yearly
Very Long Term (1-2 cycles)*	$F_{10.7}$	10%	6 solar rotations	Start & Peak of Cycle
	A_p	10%	Year	Start & Peak of Cycle

*Maximum and Minimum Values of Parameter Plus Dates of Maximum and Minimum Occurrence

Why is it that neutral atmosphere models do not do a better job of predicting orbital altitude density and number density of the constituents? A very major part of the answer lies in the inaccurate predictions of short- and long-term solar activity and geomagnetic index values used as inputs in the models. Part of the answer also lies in the selection of parameters to characterize conditions of the orbital neutral atmosphere. For example, the amount of EUV heating is represented by the 10.7 cm solar flux. The 10.7 cm flux cannot significantly heat the atmosphere. However, it has been established that there is a reasonable correlation between the EUV flux and the 10.7 cm flux. This correlation is only approximate and is not adequate for models yielding high accuracy. However, the 10.7 cm flux is measured regularly and hence is

readily available. A similar situation exists with respect to the energetic particle heating which is often measured by the geomagnetic index. This heating is related to disturbances in the earth's magnetic field, but the relationship also may not be adequate for high accuracy models.

The future development of neutral thermospheric models capable of providing more accurate predictions depends critically on replacing such indices as the 10.7 cm flux and A_p with new parameters based more closely on the physical quantities which affect the upper atmosphere. Such new parameters must directly characterize the UV/EUV flux which is the primary source of energy into the thermosphere and must indicate the thermospheric heat input into high latitude regions caused by particle precipitation. The means to develop these new parameters is available, but careful planning of future missions is required if acquisition of adequate information is to be ensured.

The exoatmospheric solar UV/EUV flux in the range from 300Å to 2000Å should be monitored to determine directly the major thermospheric heating. The precipitating particle flux (in an energy range from a few hundred eV to several keV) can be measured from low altitude polar orbiting satellites as is being done on TIROS-N and DMSP. This will allow a quantitative relationship to be established relating atmospheric response to high latitude heat sources. Finally, in order to understand the precipitation mechanisms, solar wind density and velocity should be monitored by sensors sunward of the magnetosphere. The response of the atmosphere should be monitored by density- and composition-measuring instruments having good resolution in both time and space. It should be emphasized that if unambiguous interpretation is to be made of the results of these measurements, all parameters should be measured simultaneously.

The measurements which must be made in order to ensure significant improvement in neutral density and composition models for better prediction of satellite orbit evolution are summarized in Table 2 and it is strongly recommended by this Neutral Atmosphere Subgroup that future mission plans be made to ensure simultaneously obtaining all of these significant parameters.

Table 2. Measurements required for development of significantly improved neutral density models

Parameter to be measured	Parameter Range	Location of Measurement	Purpose
Solar UV/EUF Flux	300Å-2000Å	Above ≈ 200 km	Measure primary source of energy into the atmosphere
Precipitating particle flux	Few hundred eV to few keV	Low earth orbit (Polar)	Measure high latitude heat source during magnetic storms
Solar wind density, velocity	—	Sunward of magnetosphere	Understand precipitation mechanisms
Atmospheric density composition	—	≥ 130-800 km	Determine atmospheric response to energy inputs

Note: For unambiguous understanding of observed phenomena, all quantities should be measured simultaneously.

4.3 Concluding Remarks

The prediction requirements given in Table 1 for solar 10.7 cm flux and planetary geomagnetic index parameters are based on first hand knowledge and experiences of the neutral atmosphere subgroup members as users, consultants to users, atmospheric model developers, scientists, experimenters, and predictors of solar activity to meet their own user needs. For a service or research organization concerned with or interested in trying to meet these requirements a logical question to ask concerns how serious are the users. Will the requirements simply fade away when a specific user is challenged? Will the requirements be radically relaxed or disappear when one of these organizations says to a specific user - give us the funds and we'll embark on a program to meet these requirements? The answer is probably yes to one or both questions but the degree depends upon how critical the requirement is to the particular project for which the user needs the predictions, the risks he's willing to take, the project's schedule, trade-offs on these requirements versus other project requirements, his confidence the proposal will produce results he can apply for the benefit of his project, and the costs.

Therefore, these requirements are not rigorous for all users but depend upon many factors unique to each user and his immediate project needs. For example, major decisions are made on spacecraft orbital altitudes which depend on the current inaccurate solar activity predictions. In some cases this results in less than desirable orbital altitudes relative to the scientific experimenter's requirements, higher mission success risks, provisions for much longer lifetimes than needed due to the large error bounds on the orbital altitudes estimates for the mission, and added costs for spacecraft instrumentation, operational capabilities and decay monitoring to say nothing of the embarrassment which results when an expected small risk spacecraft lifetime mission design is significantly different than expected prior to launch of the spacecraft. Thus these requirements should be taken as serious candidates for technology and scientific research program sponsorship by responsible service and research organizations.

5. USER REQUIREMENTS OF SOLAR-TERRESTRIAL PREDICTIONS FOR SPACECRAFT APPLICATIONS: RECOMMENDATIONS

The following constitutes a summary of the recommendations contained in the previous sections. It is separated by particle type to conform with the previous discussions. A warning: For an operational program, the cost of obtaining and/or using predictive techniques must be less than the cost of going to another hardware or mission design which avoids the hazard.

5.1 Energetic Particles

1. A requirement exists for a predictive technique which relates some solar or geophysical parameter (such as solar wind speed or D_{st}) to acceleration of electrons to high energies in the outer magnetosphere. The required output is: a) Spatial Distribution, b) Energy Spectra, and c) Flux Intensities.

2. Given an input distribution (spatial, energy spectrum, flux intensity) of energetic electrons in the outer magnetosphere, a model is needed which will detail the evolution of the distribution.

3. Manned applications require a short term prediction of magnetic storms and substorms. Particle acceleration and plasma injection are both major concerns.

4. A 'Disturbance Model' for prediction of flux enhancements due to solar or magnetospheric activity is required. It should have two forms: a typical storm, and a macro storm.

5. A requirement for synoptic measurements of solar wind parameters to predict intermediate term (30-60 days) averages of fluxes at synchronous altitudes exists.

6. A model which calculates the hardening of electron energy spectra in response to rapid diffusion caused by field-line loading is desired.

7. Current methods take several days to calculate the environment and dose for a new orbit. This must be shortened.

8. The long lead time (typically several years minimum) to get new data into a data base for modeling purposes must be shortened.

5.2 Solar Flare Protons

1. A predictive technique must be developed which will warn of anomalously large events (e.g., August 1972) hours or days in advance. Identification of precursors is the most probable method.

2. An accurate prediction of solar proton events based on solar parameters should be developed. It should give order-of-magnitude or better definition of the intensities and energy spectra. Timing is of concern.

3. Given an event on the sun, predict the evolution of an event from solar or interplanetary parameters.

4. Models of solar proton entry into the magnetosphere which include local-time and magnetic storm effects in rigidity calculations should be developed.

5. Determine the solar parameters which correlate well with the annual integrated fluences of unattenuated interplanetary protons with energies above 10, 30, and 60 MeV, since sunspot numbers do not.

5.3 Plasma

1. A statistical model of the ambient low-energy plasma is required, (i.e., percentages of time certain conditions will be encountered).

2. A three-dimensional model of magnetospheric plasma distribution is needed.

3. Verification of plasma drift theories and understanding of the processes which energize ionospheric ions and inject them into the magnetosphere is required in order to detail the evolution of the hot plasma distribution.

4. Expanded real-time measurements (in longitude and altitude) are desired for predictions for operational programs.

5. A better understanding of substorms and their plasma effects is required in order to ultimately produce predictive techniques.

6. Measurements of interplanetary particles and fields are desired to assist research into predictive techniques.

5.4 Neutral Atmosphere

1. Continuing synoptic observations of the Ottawa 10.7 cm flux index and the A_p geo magnetic index are required. (Details of the frequency and accuracy of updating are given in Table 1.

2. In order to develop better predictive models of the atmosphere, the following parameters should be measured simultaneously: a) Solar UV/EUV above 200 km; b) Precipitating particle flux; c) Solar wind density and velocity sunward of the magnetosphere; d) Atmospheric density and composition between 130 and 800 km.

6. MINORITY REPORT

A. L. Vampola

The following recommendation was considered by the working group but was not formally accepted. It is included here because of the enthusiasm with which it was received by some participants in some of the other groups and because an essentially identical recommendation was offered for the group's consideration by a modeler.

Recommendation: That a centralized catalog of 'State of the Art' models and predictive techniques in solar-terrestrial phenomena be established and maintained by one of the prediction or data archival service agencies (such as SESC, WDC-A, or AFGWC).

The rationale behind this recommendation is that the 'Corporate Memory' in spacecraft engineering seems to reside in old proposals and contract specifications. The normal evolution of an engineering career is to become part of management after a number of years of design engineering. Technologies become obsolete and so do models and predictive techniques. A new engineer is usually forced to rely on documents inherited from the previous occupant of his 'slot' who has moved on and is no longer keeping track of the minutiae of his previous position. As a result, it is not uncommon to see models or predictive techniques written into contracts ten or more years after they have been supplanted.

By having a central catalog for these techniques/models, the latest version would be readily identified by potential users. It would be incumbent upon the modelers, themselves, to ensure that the latest versions of their works were listed in the catalog. Distribution of computer programs or large data bases required by some models would continue as at present: through direct contact between the user and the modeler. In the case of substantial changes in modeling or predictive techniques, some international group (similar to the present workshop or established single interest scientific bodies) could make the decision to abandon one model or technique and supplant it with another in the catalog.

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